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NOVEL STRATEGY FOR COMPENSATING CURRENT DETERMINATION IN SINGLE PHASE ACTIVE POWER FILTERS

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Abstract: **-** This paper reports a novel strategy for analysing a single phase power system feeding A non-linear load. This strategy is based on a new theory to transform the traditional single phase power system into an equivalent two-axis orthogonal system. This system is based on complementing the single phase system with a fictitious second phase so that both of the two phases generate an orthogonal power system. This would yield a power system which is analogous to the three phase power system but with the phase shift between successive phases equal to $\pi/2$ instead of $2\pi/3$.
Application of this novel approach makes it possible to use the complex or Gauss domain analytical method in a similar way to the well known method of instantaneous reactive power for the three phase power system instigated by Akagi et al in 1984.Thus, for the fictitious two-axis phase power system, the concept of instantaneous active and reactive power could be instigated. Moreover, the concept of instantaneous power factor could be defined. The novel strategy of power system analysis outlined in this paper is applied to a single phase power system feeding a non-linear load in conjunction with an active power filter. The latter serves the purpose of compensating for either of the instantaneous reactive power or the harmonic current distortion in the single phase power system under investigation or for compensating of both. Experimental results demonstrated the effectiveness of the novel single phase power system analysis reported in this paper.

Key-Words: - phase power systems, orthogonal transformation technique, harmonic distortion and reactive power compensation

1 Introduction

In this section the orthogonal transformation technique applied to a single phase power system instigated by Akagi et al, (Akagi Kanazawa and Nabae, 1983) is described. By adopting this technique expressions for the reference currents used in an active power filter for the compensation of harmonic distortion or reactive power or both, are derived.

Consider a single phase power system which is defined by its input voltage and input current as follows:

$$v_{Re}(t) = V \cos \omega t$$
$$i_{Re}(t) = I \cos (\omega t - \Phi) \qquad (1)$$

Where V and I respectively are the peak values of the voltage and current, ω is the angular frequency of the power supply and Φ is the phase shift between voltage and current.

The power system described by Eq.(1) is termed as the real part in a complex power system and is complemented by a fictitious/imaginary phase defined as follows:

$$V_{im}(t) = V \sin \omega t$$
$$I_{im}(t) = I \sin (\omega t - \Phi) \qquad (2)$$

Comparing Eqs (1) and (2), it is obvious that the imaginary or fictitious phase of the voltage or current in a single phase power supply can be created in the time domain by shifting the real component on the time axis to the right by an equivalent phase shift of $\pi/2$.
According to Eqs(1) and (2), the α-β orthogonal co-ordinate systems for both of the voltage and current are defined as follows:

$$v_\alpha = v_{Re}(t) \text{ and } v_\beta = v_{im}(t)$$
$$i_\alpha = i_{Re}(t) \text{ and } i_\beta = i_{im}(t) \qquad (3)$$

According to (Akagi, Kanazawa and Nabae, 1983) , each of the α and β components of the voltage and current are combined to form a vector, x(t).
This vector can be represented by the following equation:

$$x(t) = x_\alpha + x_\beta\, e^{j\pi/2}$$
$$= x_{Re}(t) + x_{im}(t)\, e^{j\pi/2} \qquad (4)$$

This vector is represented in the Gaussian complex domain as a four sided symmetrical trajectory, Fig.1.

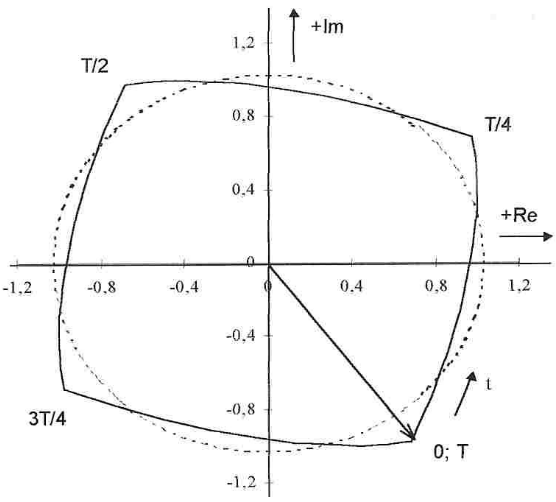

Fig1. Trajectory of vector x(t)

Because of the symmetry of the x(t) trajectory shown in Fig.1, it is evident that the voltage and current investigation for the complex power system (including both of real and imaginary voltage and current components), could be carried out within quarter of the periodic time of the voltage and current waveforms (T/4). Thus, Fourier transforms applied for the harmonic analysis of non-sinusoidal waveforms could be carried out during this time interval only as it will be shown later. Fig.2 shows the arrangement of the real and fictitious/imaginary circuits of the complex single phase power system under investigation. As it is shown on this figure, the real and fictitious circuits should be synchronised by the so called "SYNC" signal. This implies that the x(0) is a priori zero.

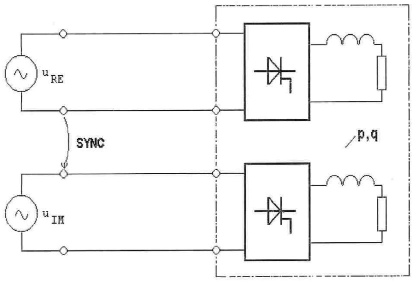

Fig.2 Real and fictitious circuits of the complex single phase power system

2 Instantaneous Reactive Power

In this section the use of the p-q-r instantaneous reactive power method, described in references (Dobrucky, 1985), (Kim and Akagi, 1999) and Akagi, Kanazawa and Nabee, 1984), for compensation of the reactive power and harmonic filtering is explained.

Consider a single phase power system with a co-sinusoidal voltage supplying a solid state controlled rectifier, thus yielding a non-sinusoidal supply current waveform. The supply current is assumed to have a square waveform. Thus, the supply voltage and the fundamental component of the supply current could be written as:

$$v_{Re}(t) = V \cos \omega t$$

$$i_{1Re}(t) = I_1 \cos (\omega t - \pi/3) \tag{5}$$

The supply voltage and current waveforms as well as the fundamental current waveform are depicted in Fig.3.

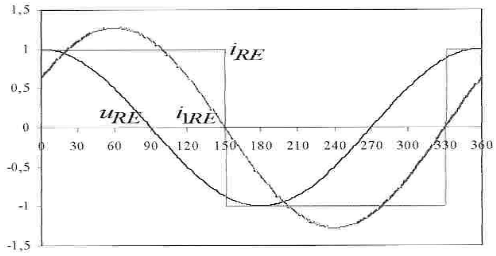

Fig.3 Supply voltage, current waveforms and the fundamental current component waveform for a single phase power circuit consisting of a co-sinusoidal voltage supply feeding a solid state controlled rectifier

The imaginary/fictitious components of the waveforms shown in Fig.3 are depicted in Fig.4.

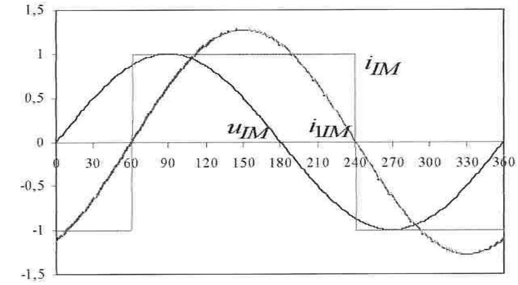

Fig.4 Imaginary/fictitious components of the supply voltage, current waveforms and the fundamental current component waveform for a single phase power circuit consisting of a co-sinusoidal voltage supply feeding a solid state controlled rectifier

The voltage and fundamental current components are given as:

$$v_{im}(t) = V \sin \omega t$$

$$i_{im}(t) = I_1 \sin (\omega t - \pi/3) \tag{6}$$

The instantaneous active and reactive power equations for the complex power system under consideration are given in the α-β domain, as described in references (Akagi, Kanazawa and Nabae, 1983),(Kim and Akagi, 1999) and (Akagi, Kanazawa and Nabae, 1984), as follows:

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$
$$q = v_\alpha i_\alpha - v_\beta i_\beta \qquad (7)$$

Fig.5 depicts the time variation of p and q for the complex single phase power system under consideration. In this figure P_{AV} and Q_{AV} respectively are the average values of the active and reactive power.

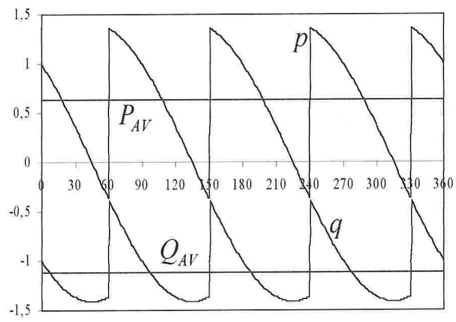

Fig.5 Instantaneous and average values for p and q for a complex single phase, the real component of which consists of a co sinusoidal voltage supply feeding a solid state controlled rectifier

The instantaneous power factor, Φ, is defined as:

$$\Phi = \tan^{-1} (q/p) \qquad (8)$$

It is important to point out that the values of p, q and Φ in Eqs (7) and (8) are instantaneous values.

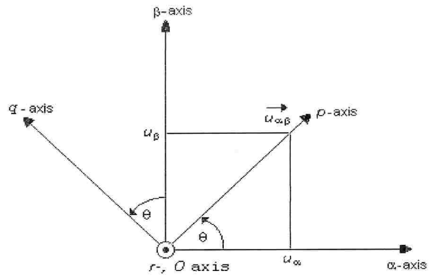

Fig.6 Voltage in a complex single phase power system represented in fixed and rotating frames of reference

The p-q-r theory is introduced in references (Kim and Akagi, 1999) and (Kim, Blaabjerg , Bak-Jensen and Choi, 2001), where the current, voltage and power equations are projected in p-q-r rotating frame of reference. Fig.6 shows the voltage components in both of the fixed α-β and rotating p-q frame of reference for a single phase power system.

In Fig.6, $v_{\alpha\beta}$ is defined as:

$$v_{\alpha\beta} = \sqrt{v_\alpha{}^2 + v_\beta{}^2} \qquad (9)$$

Angle, θ is defined as:

$$\Theta = \tan^{-1} (v_\alpha/v_\beta) \qquad (10)$$

The r-axis is considered to be identical to the zero axis, hence the voltage transformation equation from the fixed frame of reference α-β to the rotating frame of reference p-q-r, can be written as:

$$\begin{bmatrix} v_p \\ v_q \\ v_r \end{bmatrix} = 1/v_{\alpha\beta} \begin{bmatrix} v_\alpha & v_\beta & 0 \\ 0 & 0 & 0 \\ 0 & 0 & v_{\alpha\beta} \end{bmatrix} \cdot \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} v_{\alpha\beta} \\ 0 \\ 0 \end{bmatrix} \qquad (11)$$

The currents in the rotating frame of reference, i_p, i_q and i_r are related to the currents in the stationary frame of reference, i_α and i_β by similar equations as the voltage equations in Eq.11.

Moreover, the following relations can be derived in the p-q-r rotating frame of reference:

$$p_{\alpha\beta} = v_{\alpha\beta}\, i_{\alpha\beta} = v_\alpha\, i_\alpha + v_\beta\, i_\beta = p$$

$$v_p = v_{\alpha\beta}$$

$$v_q = v_r = i_q = i_r = 0 \qquad (12)$$

$$i_p = i_{\alpha\beta}$$

$$p = v_p\, i_p$$

3 Derivation of Reference Current Expressions for the Active Filter

In this section instantaneous expressions for the reference currents for an active power filter to compensate for the harmonic distortion or reactive power or both in the single phase power system under investigation are derived.

Because of the symmetry of the complex voltage and current vectors trajectories, Fig.1, the average value of the active and reactive powers for both of the real and imaginary/fictitious phases can be evaluated from Eq.7 as follows:

$$P_{RE\,AV} = P_{AV}/2 = 2/T \int_0^{T/4} (v_\alpha i_\alpha + v_\beta i_\beta)dt$$

$$(13)$$

$$Q_{RE\,AV} = Q_{AV}/2 = 2/T \int_0^{T/4} (v_\alpha i_\alpha - v_\beta i_\beta)dt$$

According to (Akagi, Kanazawa and Nabae, 1983), the instantaneous expressions for the active and reactive power in the real phase of the single phase power system under analysis are given as:

$$P_{RE} = (v^2_\alpha / v^2_{\alpha\beta})p$$

$$(14)$$

$$q_{RE} = (- v^2_\beta / v^2_{\alpha\beta})q$$

The real phase average value, fundamental and ripple components of the active and reactive power are extracted from Eqs (13) and (14) and are depicted in Fig .7 and Fig.8 respectively.

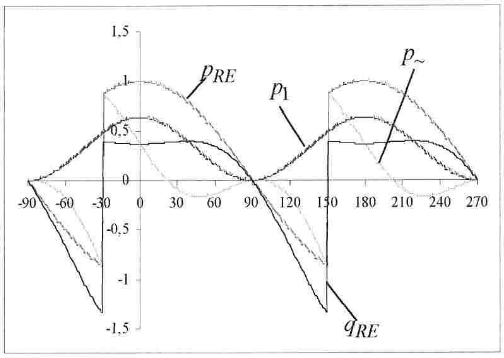

Fig.7 Components of the active power for the real phase of the complex single phase power system

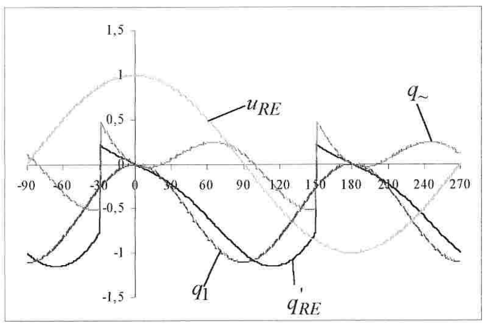

Fig.8 Components of the reactive power for the real phase of the complex single phase power system

The real phase current, i_α, can be derived from Eq.7 as follows:

$$i_\alpha = 1/v_{\alpha\beta}^2 \, (v_\alpha\, p - v_\beta\, q)$$

$$= 1/v_{\alpha\beta} (v_\alpha (P_{AV} + p_\sim) - v_\beta (Q_{AV} + q_\sim)) \quad (15)$$

In Eq.15, $p_\sim$ and $q_\sim$ respectively are the ripple active and reactive power components.

Reference current for the active filter of the single phase system under consideration can assume different expressions depending on the special requirements of compensating for the reactive power or filtering the distortion harmonics. Three special cases are listed below:

i) <u>Reference current for distortion harmonic filtering and reactive power compensation</u>

$$i_{ref} = 1/v_{\alpha\beta}^2 \, (v_\alpha \, p_\sim - v_\beta \, q)$$

$$= 1/v_{\alpha\beta}^2 \, (v_\alpha \, (p-P_{AV}) - v_\beta \, (q-q_{AV})) \qquad (16)$$

ii) <u>Reference current for average reactive power compensation</u>

$$i_{ref} = 1/v_{\alpha\beta}^2 \, (-v_\beta \, Q_{AV}) \qquad (17)$$

iii) <u>Reference current harmonic distortion compensation</u>

$$i_{ref} = 1/v_{\alpha\beta}^2 \, (v_\alpha \, p_\sim - v_\beta \, q_\sim) \qquad (18)$$

4 Experimental Results

A test rig was set up to verify the theoretical derivations above. An active power filter is implemented with the current reference of Eq.(15) used as an input to the filter and the digital signal processing of the voltages and currents is implemented using a 32 bit floating point DSP,TMS320C31. The configuration of the experimental setting is shown in Fig.9.

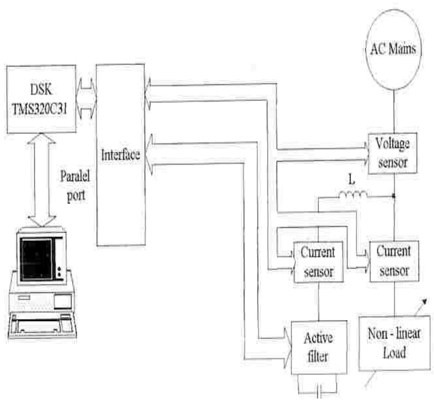

Fig.9 Block Diagram of the Experimental Setting

The single phase power system under experimentation is a diode bridge rectifier with an RL load connected to the dc side. The ac to dc converter is rated at 25 kVA. An inductor, L, with a value of 1.2 mH and a capacitor with a value of 10,000 µF are used as dc output filter. The output current of the active power filter is controlled by a hysteresis comparator to confine the switching frequency to 15 kHz.

Fig.10 shows the waveforms of the load current, the compensating current of the active power filter and the

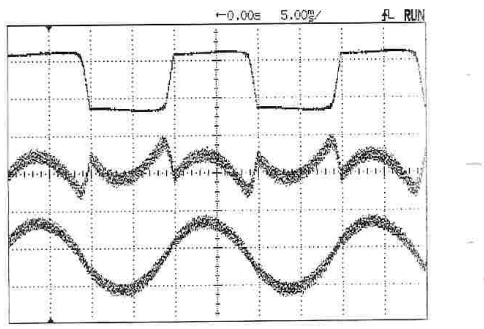

Fig.10 Supply current to the single phase power system under consideration before (top) and after (bottom) the implementation of the active power filter

supply current. It is clear that active power filter performed its task of compensating for the harmonic distortion as the supply current is converted to a pseudo-sinusoidal waveform from its original square shape waveform. The top waveform in Fig.10 shows the original supply current waveform and the bottom waveform shows the supply current wave form after the implementation of the active power filter. The middle wave form is the compensating current of the active power filter.

5 Conclusions

A novel strategy, orthogonal transformation technique, is used to yield reference current expressions for the active power filter of a single phase power supply feeding a solid state power converter, in terms of the supply voltage and current. The power active filter control strategy could compensate for either the harmonic distortion of the supply current or the reactive power or both.

Experimental results demonstrated the effectiveness of the novel active power filter control strategy.

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